THREE DIMENSIONAL NUMERICAL MODELLING OF EFFECTS OF
SUBSIDENCE ON ESCARPMENTS

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ABSTRACT

Significant coal reserves in New South Wales lie under areas with steep topography such as valley slopes and cliffs. Subsidence predictions are difficult to make for these locations as existing empirical databases cannot cover all permutations of topography and mining geometry. Two dimensional numerical model alternatives are of limited applicability. Consequently a novel three-dimensional numerical model is developed including the detailed panel layout, realistic rock mass properties including the full stratigraphy, geof behaviour and actual surface topography. Model results show the same trends as subsidence measurements from Basi Bone Colliery in the Western Coalfield of New South Wales.

INTRODUCTION

Significant coal reserves in New South Wales lie under steep slopes and cliffs. Mining has been restricted to within conservative angles of draw from significant topographic features. Considerable potential exists to improve extraction rates through improved understanding of the strata mechanisms involved when a steep slope or cliff is undermined. In late 1989 the NSW Department of Mineral Resources initiated a two year research project 'Effects of Subsidence on steep topography and cliff lines' which focussed on Longwall extraction at the Basi Bone Colliery in the Western Coalfield of NSW. This paper describes the three-dimensional numerical modelling component of the project. Kay and Carter (1992) give background information on the site and details of the subsidence monitoring.

Empirical subsidence prediction techniques such as developed by the National Coal Board (1975) are generally restricted to cases where the ground surface is essentially horizontal. These empirical charts cannot be consistently used for locations with steep topography such as valleys with relatively steep slopes. The previous numerical modelling studies of the subsidence characteristics of steep topography (e.g. Franks and Godfrey, 1966, Jones et al., 1960, Pake, 1991), were two-dimensional. These studies showed that the presence of steep ground affects the horizontal movements and ground strains more than vertical movements and tilts. Two-dimensional (plane strain) analysis can only model planes parallel to the cliff lines. Planes at right angles to the cliff lines cannot be correctly represented in two dimensions as they are effectively infinitely wide.

The centre lines of the Longwall panels studied at Basi Bone Colliery are typically at right angles to the cliff lines, precluding two-dimensional analysis. Extensive and accurate three-dimensional data from the monitoring exercises provided further motivation for the development of a full three-dimensional model. The resulting novel hybrid approach combines the best features of the displacement discontinuity method and finite elements. Displacement discontinuity and finite elements modelled the excavation plane and the surface topography respectively. This allows the sophisticated numerical model to incorporate the actual mine layout with roadway details, realistic rock properties including the full stratigraphy, geof behaviour and loading, and the actual surface topography. This level of detail has not been previously included in a geotechnical model.

A number of alternative surface geometries were analysed during the project. A selection of results from the 'back-analysis' of one of the monitoring sites, "Valley 2", are presented here. Other geometries represented several 'what if' topography scenarios, including the effects of mining at greater depth and mining under an isolated cliff.

Numerical modelling of mining subsidence is notoriously difficult due largely to the complexity of the rock mass behaviour. The following sections discuss the main issues involved in modelling subsidence and describe the philosophy and procedure used to construct the model.

CONCEPTUAL MODEL

The art of conceptual modelling involves simplifying the complex properties of the prototype to the essential components. The best conceptual model is the simplest model that includes these key components and fits the observed behaviour of the prototype. A modeller must take care to strike a balance between model realism and model complexity. Computer programs can produce answers to an impressive degree of accuracy, but are these simply very precise answers to the wrong problem? An unnecessarily complex model leads to commensurate demands on data preparation and computer resources and additional uncertainties resulting from unknown material properties.

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Total extraction mining systems involve caving of the immediate roof of the excavation and subsequent load transfer to the resultant caved waste material, commonly known as "goaf" or "void". Although this involves rock fabric disintegration, bed separation, block sliding and rotation, etc., it is impossible to incorporate the detailed mechanics of deformation in a model.

Experience shows that transversely isotropic linear elastic models can realistically represent the overall response of the rock mass. Wardle and Ennor (1969) demonstrated the shortcomings of subsidence predictions based on isotropic rock properties. (t) the subsidence profile is much flatter than is normally observed and (2) laboratory models must be reduced by an order of magnitude or more to match measured maximum subsidence. However rock mass properties based on laboratory tests generally predict subsidence that is an order of magnitude smaller than observed values. Consequently it is necessary to 'back-calculate' representative parameters by matching numerical model results to prototype measurements.

The properties of the goaf material play a major role in determining maximum subsidence characteristics for supercritical conditions and pillar and abutment loading, as illustrated by case studies (Wardle and McNabb, 1965, Wardle and Klenowki, 1969). The goaf is modelled in this case by an equivalent continuum.

**NUMERICAL MODEL**

**CHOICE OF NUMERICAL METHOD**

General numerical methods such as Finite Elements or Boundary Elements require inordinate amounts of computer time and storage to solve practical threedimensional problems with the necessary geometrical detail of actual mine layouts including multiple extraction panels, roadways, chain pillars and so on. A special form of boundary element method, the displacement discontinuity method (DDM), has been developed for tunnel excavations, i.e., excavations that are characterized by their negligible thickness in comparison to their plan dimensions. The method assumes the excavations are represented by thin slits of the same plan area as the excavations. The relative movement between the roof and the floor is treated as a displacement discontinuity.

Computer programs for three-dimensional displacement discontinuity analysis offer economical and reliable solutions at a fraction of the cost of more general methods and can solve much larger problems than is possible with alternative programs. Early DDM programs were restricted to a homogeneous rock mass. In the last decade a computer program (MINLAY-MINing of LAYERed rock) has been developed that models the rock mass as a number of parallel layers with distinct anisotropic elastic properties (Wardle, 1984, 1989). The interfaces between layers do not need to be discretized and the unloading upper surface of the system can be used to take account of ground surface effects. The ground surface of a MINLAY model must be flat due to the paralled layering. A new program, SUBSOL, has been recently developed from MINLAY with additional features specifically developed for subsidence engineering, including surface topography. The best features of the displacement discontinuity approach have been combined with finite elements that were used in this case to model the surface topography.

This hybrid approach has solved problems beyond the capacity of any current alternative.

**MINE LAYOUT AND VALLEY GEOMETRY**

Figure 1 is an overall view of the modelled panel layout. The longwall face length is 205 m (measured from gateroad centres). The chain pillars are 23 m wide and were modelled using linear elastic coal properties. SUBSOL can model yielding coal, but for this project the yield of the chain pillars was not expected to be a major factor. The extracted seam thickness was 2.5 m. The emphasis of the model was on predicting the subsidence resulting from extraction of Longwall Panel 8.

Figure 2 shows a view of the modelled valley. This represents a section taken through the panel centreline and shows only half of the area modelled. The jagged appearance is a consequence of removing finite elements to produce this figure. The deleted elements extend in all three directions. The depth of cover for the plateau area is 230 m and 130 m for the valley.

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A coupled displacement discontinuity method/finite element model was developed as described above. The upper part of the rock mass (down to 100 m below the plateaus) was modelled by three-dimensional finite elements. The remainder of the rock mass was modelled using the displacement discontinuity method. The mine layout is approximated in plan by a uniform rectangular grid of displacement discontinuity elements. The element size (5 m by 5 m) is chosen for convenience and approximates the actual roadway width by one element width. The area of the excavation plane modelled consists of 120 x 120 elements = 600 m x 600 m.

ROCK MASS PROPERTIES

The back-calculated parameters used in this study are based on earlier modelling carried out at the nearby Kuruwara Colliery (Kay et al. 1991). The stratigraphy used in the model incorporates the significant material property contrasts given by UCS tests conducted by AIICF at the nearby Kuruwara Colliery (Department of Minerals and Energy, 1990).

The pre-mining vertical stress gradient is taken as 0.25 MPa per metre of overburden, giving a vertical pre-mining stress of about 5 MPa. A 1:1 vertical to horizontal stress ratio was used in the analyses presented here.

RESULTS

Subsidence predictions were obtained for a number of face positions (Kay, 1991). Results are presented for two face positions: (i) 30 July 1990; (ii) 60 m to the plateaus and (iii) 120 m to the plateaus. The displacement results presented are the increments due to extraction of Panel I.

The following figures show the predicted vertical (Z), horizontal E-W (X) and horizontal N-S (Y) displacements. The displacement magnitudes are in millimetres and are positive for the directions shown on the figures. (i.e. Z is positive up, X to the east and Y to the North).

Figure 3 shows the displacements for 30 July, 1990. Figure 4 shows the displacements for the fully extracted panel. The model results indicated the same displacement trends as were monitored. The maximum Z and X displacements occur along the panel centre-line. The maximum vertical subsidence occurs at the base of the valley. The maximum Y (transverse) displacements occur between the centre-line and the panel rib. The locations of the maxima are consistent with empirical data for flat topography.

The valley however produced horizontal movements opposite to those commonly observed with flat topography. Figure 5 shows the horizontal displacement pattern observed above the panel (Kay, 1991). This figure is not drawn to scale. The monitored Longwall panel (6) retreated to the West (left hand side of figure). As the face approached the eastern cliff the E-W horizontal displacements (X) were towards the valley centrelne. This was despite the greatest subsidence occurring to the East on the plateaus. This trend continued as the face passed under the eastern cliff. This contrasts with the usual pattern of movements commonly observed for flat topography, i.e. the horizontal displacement is towards the cliff. The final position of...
the cliff was to the West.

The maximum observed vertical subsidence was about 1.5 m. The maximum subsidence over the chain pillars was about 0.1 m which confirmed the earlier decision to not include pillar yield in the model.

CONCLUSIONS

For the first time mining induced subsidence has been realistically modeled with full three dimensional topographic effects. The novel hybrid approach has produced the most sophisticated numerical model used for subsidence back-analysis and prediction. The model included the actual mine layout with roadway details, realistic rock behaviour including goaf formation and loading, and actual surface topography. This level of detail has not previously been incorporated in a three-dimensional model.

The numerical model predicted the same trends observed during the monitoring exercises. The technique can confidently be used to predict stresses, strains and displacements resulting from undermining of steep topographic features.

SUSOL is continuing to be developed to realistically model stratified coal deposits. Given the limited time and resources no attempt was made to model the detailed collapse behaviour of the cliffs. The cliff mechanics could be modelled in more detail with joint elements and non-linear continuum properties.

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